Electromagnetically induced transparency for Λ - like systems with a structured continuum

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Electric susceptibility of a laser-dressed atomic medium is calculated for a model Λ-like system including two lower states and a continuum structured by a presence of an autoionizing state or a continuum with a laser-induced structure. Depending on the strength of a control field it is possible to obtain a significant reduction of the light velocity in a narrow frequency window in the conditions of a small absorption. A smooth transition is shown between the case of a flat continuum and that of a discrete state serving as the upper state of a Λ system.

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It has been known for a long time that atoms in the Λ configuration irradiated by two laser fields may exhibit peculiar dynamical properties. In particular the population may be trapped in the so-called dark state, being a combination of the two lower states. It constitutes a basis for subtle coherent dynamical manipulations like an efficient population transfer (stimulated Raman adiabatic passage - STIRAP), robust against any broadening of the upper state [1, 2]. Effects of such a type are present also in the case in which the upper state of a Λ configuration has been replaced by a continuum [3, 4, 5] or, in strong laser fields, by a set of coupled continua [6].

Dynamical effects in particular atoms are reflected in unusual light propagation effects in atomic media. One of the most important propagation effects in a medium of atoms in the Λ configuration is the electromagnetically induced transparency (EIT), which consists in making the medium transparent for a weak probe laser beam by irradiating it by a strong copropagating control beam [7, 8]. Instead of an absorption line there appears a transparency window and a normal dispersion. By switching the control field off when the pulse is inside the sample one can slow the light pulse down and finally stop or store it [9, 10, 11]. The photon energy of the signal is transferred to the control beam while the information about the pulse is written down in the form of a coherence (nondiagonal element of the density matrix) between the two lower states. Switching the signal on again results in reading the information out: the pulse is reconstructed in a coherent way.

A natural question arises whether similar propagation effects may occur in the case of a continuum serving as an upper state. Some answer has been given by van Enk *et al.* [12, 13], who considered a general case of two beams propagating inside the medium. Their conclusion was that a necessary condition for EIT was that the asymmetry parameter in the continuum model was zero. In their case the losses due to photoionization are of second order with respect to the probe field. Thus, in the linear approximation with respect to the probe beam and neglecting propagation effects for the strong control beam, one still may apply the standard approach in which the probe propagation is discussed in terms of an atomic susceptibility. Below we give analytic expressions for the susceptibility in the case of the bound-continuum dipole matrix elements being modeled according to Fano autoionization theory [14]. By changing the Fano asymmetry parameter we pass from the case of a flat continuum to that of a discrete and broadened bound state. We examine the shape of the transparency window depending on the amplitude of the coupling field.

We consider a generalization of a Λ system in which the upper state is replaced by a continuum: an atomic system including two lower discrete states b (initial) and c and a continuum E coupled with the state b by a weak probe field $(\frac{1}{2}\epsilon_1(z,t)\exp[i(k_1 z - \omega_1 t)] + c.c$ and with the state c with a relatively strong control field $\epsilon_2 \cos \omega_2 t$. The continuum may have a Fano density of states, due to a configurational coupling with an autoionizing state or to a structure induced by another laser [15]. As usually in EIT, the control field, the propagation effects for which are neglected, dresses the atomic medium to create new conditions for the propagation of the probe pulse. The evolution of the atomic system is described by the von Neumann equation, which after transforming-off the rapidly oscillating terms and making the rotating-wave approximation is reduced in the first order perturbation with respect to the probe field to the set of the following equations for the density matrix σ

$$i\hbar\dot{\sigma}_{Eb} = (E - E_b - \hbar\omega_1)\sigma_{Eb} - \frac{1}{2}d_{Eb}\epsilon_1 - \frac{1}{2}d_{Ec}\epsilon_2\sigma_{cb},$$

$$i\hbar\dot{\sigma}_{cb} = (E_c + \hbar\omega_2 - E_b - \hbar\omega_1 - i\gamma_{cb})\sigma_{cb} - \frac{1}{2}\epsilon_2^* \int d_{cE}\sigma_{Eb}dE. \tag{1}$$

In the above equation d is the dipole moment and γ_{cb} is a phenomenological relaxation rate for the coherence σ_{cb}. Stationary solutions of Eqs (1) can be found by first expressing σ_{cb} in terms of σ_{Eb} and then by solving the integral equation for the latter. The component of the polarization of the medium connected with the $b - E$ coupling is

$$P^+(\omega_1) = N \int d_{bE}\sigma_{Eb}dE = \epsilon_0 \chi(\omega_1)\epsilon_1(\omega_1), \tag{2}$$

with ϵ_0 being the vacuum electric permittivity, N - the atom density and with the medium susceptibility given by

$$\chi(\omega_1) = -\frac{N}{2\epsilon_0}\left(R_{bb} + \frac{1}{4}\frac{\epsilon_2^2 R_{bc}R_{cb}}{E_b + \hbar\omega_1 - E_c - \hbar\omega_2 + i\gamma_{cb} - \frac{1}{4}\epsilon_2^2 R_{cc}}\right). \tag{3}$$

The function $R_{ij}(\omega_1)$, $i, j = b, c$, is given by

$$R_{ij}(\omega_1) = \int_0^\infty \frac{d_{iE}d_{Ej}}{E_b + \hbar\omega_1 - E + i\eta}dE, \tag{4}$$

where $\eta \to 0^+$ assures the correct behavior at the branch cut. The presence of an autoionizing state coupled with the continuum results in a modification of the density of the continuum states, which leads to the following Fano formula

for the bound-structured continuum dipole matrix element

$$|d_{iE}|^2 = B_i^2 \frac{(E - E_a + q\gamma)^2}{(E - E_a)^2 + \gamma^2}, \tag{5}$$

where E_a and γ characterize the position and width of the autoionizing resonance, q is the Fano asymmetry parameter and B_i is the bound-flat continuum matrix element. We assume that the matrix elements for the states b and c differ only by a constant factor $B_{b,c}$, i.e. the presence of the autoionizing state is the only reason for the continuum to exhibit any structure. For real systems the energy dependence of the matrix element is more complicated, in particular an additional form factor is necessary to account for a threshold behavior or a correct asymptotic properties. Taking such a form factor into account is not essential in an approach like ours, in which we concentrate on the frequency dependence of the susceptibility in a narrow band close to the resonance.

If the lasers are tuned sufficiently far from the ionization threshold and so is the localization of the autoionizing state we can extend the lower limit of the energy integral to $-\infty$ and get from Eqs (4) and (5)

$$R_{ij}(\omega_1) = B_i B_j \pi \frac{\gamma(\hbar\omega_1 - E_a)(q^2 - 1) + 2q\gamma^2 - i(\hbar\omega_1 - E_a + q\gamma)^2}{(\hbar\omega_1 - E_a)^2 + \gamma^2} \tag{6}$$

It is possible to evaluate the width of the structure in the susceptibility given by Eqs (3) and (6) if it is significantly smaller than an autoionizing width, i.e $\gamma >> q\omega_1$. The width for $q >> 1$ is in atomic units of order of $\epsilon_2^2 q^2$. This result is to be compared with the width of the transparency window for EIT in a typical Λ system, i.e. one with a discrete broadened upper state. The width of the latter window is in atomic units of order of ϵ_2^2/Γ, Γ being the relaxation rate for the nondiagonal element of the atomic coherence. One can see that for the same control fields the transparency window here is much more narrow. For a typical value of $\Gamma \approx 10^{-8}$ a.u. we need $q \approx 10^4$ to make the windows in the two cases comparable. The light absorption in the case of the continuum is by a few orders of magnitude weaker (again except for very large q) than in the case of a discrete upper level but due to the transparency window being narrow the dispersion can be very steep, so a significant light slowdown is possible.

As an illustration of the above formalism we show the atomic susceptibility calculated from Eqs (3) and (6). We have taken $\gamma = 10^{-9}$ a.u.$\approx$ 6.6 MHz. The values of the field amplitude ϵ_2 ranged from 10^{-9} to 10^{-6} a.u., i.e. the width $2\pi\epsilon_2^2 B_j^2/4$ of the lower states, induced by the bound-continuum coupling for the flat continuum (without the Fano factor) would be of order of $10^{-8}\gamma$ to $10^{-2}\gamma$. The values of the parameters B_j were taken arbitrarily $B_1 = 2$ a.u., $B_2 = 3$ a.u. The atomic density was $N = 0.67 \times 10^{12}$ cm^{-3}. The asymmetry parameter q was of order of 10-100. The position of the states was taken $E_a = -E_b/2 = -E_c = 0.1$ a.u.$=$ 2.72 eV. The relaxation rate γ_{cb}, possibly due to the spontaneous emission from the level c or to an incoherent ionization channel by the field ϵ_2 from the level b, was neglected.

In Fig. 1 we show the medium susceptibility for $q=10$ and $\epsilon_2 = 0$. As expected, a normal dispersion is observed except close to the resonance, together with a single absorption line. Note that the maximum values of both the real and imaginary parts of χ are smaller than 10^{-9}. Fig. 2 shows the susceptibility after switching on a relatively strong control field $\epsilon_2 = 10^{-6}$ a.u. Note the transparency window of the width of order of γ and the corresponding interval of a normal dispersion at a resonance frequency. Due to the Fano asymmetry the curves in the figure lack symmetry too. The group index $n_g = 1 + \frac{\omega_1}{2}\frac{d}{d\omega_1}\text{Re}\chi(\omega_1)$, being the factor by which the probe signal velocity is reduced, is only about 1.1. Figs 3 and 4 show how the frequency window is narrowed for smaller control fields. The widths are of order of $10^{-2}\gamma$ and $10^{-4}\gamma$ respectively, while the corresponding group indices are of order of 10 and 1000. The spectral width of the laser beam needed in the latter case is however not yet accessible. The effects of a reduced absorption and a steep normal dispersion are made stronger if the Fano parameter q is increased. In Fig. 5 we show the suspecptibility for $q = 100$ and $\epsilon_2 = 10^{-9}$ a.u. (q has been increased and ϵ_2 has been decreased by the factor of 10 compared with Fig. 4). Note that absolute values of χ are increased by two orders of magnitude compared with those of Fig. 4 while the transparency window is the same. This means that the group index is about 10^5.

We have investigated the optical properties of an atomic medium in the Λ configuration in which the upper state is replaced by a continuum. Such a system exhibits properties similar to those of a typical Λ system, except that the orders of their magnitude are changed. Here the windows of a reduced absorption (which is in general much smaller for the systems examined here) and of a normal dispersion are much more narrow, if the control fields are not made stronger. The dispersion curve in the transparency window may still be steep, which gives rise to a significant light slowdown. By increasing the Fano asymmetry parameter by a few orders of magnitude we smoothly pass to the case of a typical Λ system.

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Figures

FIG. 1: The real and imaginary parts of the susceptibility in the case of $\epsilon_2 = 0$ and $q = 10$. Zero frequency corresponds to the resonance with the autoionizing state.

FIG. 2: As in Fig.1 but for $\epsilon_2 = 10^{-6}$ a.u.

FIG. 3: As in Fig.1 but for $\epsilon_2 = 10^{-7}$ a.u.

FIG. 4: As in Fig.1 but for $\epsilon_2 = 10^{-8}$ a.u.

FIG. 5: As in Fig.1 but for $\epsilon_2 = 10^{-9}$ a.u. and $q = 100$.